TEN-YEAR RELIABILITY ASSESSMENT OF PHOTOVOLTAIC WATER PUMPING SYSTEMS IN MEXICO

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ABSTRACT

Between 1994 and 2000, 206 photovoltaic (PV) water pumping pilot systems were installed in Mexico as part of the Mexican Renewable Energy Program (MREP). MREP is a collaborative program sponsored by the U.S. Agency for International Development (USAID) and the U.S. Department of Energy (DOE) that has been managed by Sandia National Laboratories (Sandia). Various Mexican program partners have collaborated with MREP, including the Fideicomiso de Riesgo Compartido (FIRCO) for the deployment of PV systems for agriculture. After ten years of MREP PV system implementation, a review was conducted of 46 installed systems from late 2003 to early 2004. Typical system configurations include a PV array, pump, controller, inverter (only for ac pumps), and overcurrent protection. After performing the technical evaluations, it was found that over 3/5 of the surveyed systems were operating appropriately after as much as 10 years of operation. This paper details the results analysis from 46 PV water pumping systems assessed in the Mexican states of Baja California Sur, Chihuahua, Sonora, and Quintana Roo, and characterizes technology reliability.

1. INTRODUCTION

Most MREP PV water pumping systems were installed in the northern deserts of Mexico in rural areas that suffer from severe water shortages. Underground water is indispensable in these areas to meet daily water needs for domestic, crop, and livestock uses. Traditional water pumping systems powered by diesel or gasoline engines have been used for decades. However, the cost and transportation of fuel, and also engine maintenance, make conventional water pumping technologies expensive for people living in rural areas. One solution to reduce total system and operational cost of conventional water pumping systems is to replace them with PV systems. These may offer a less expensive life-cycle-cost option in many cases. Line extension of the utility grid is prohibitively costly at over US$9,000/km, depending on terrain. Distance to the grid ranges from a few to dozens of kilometers in many cases.

Between 1994 and 2000, two hundred and six pilot PV water pumping systems were installed mainly in four Mexican states as part of the Mexican Renewable Energy Program (MREP). MREP is designed to expand the use of renewable energy technologies for Mexico's rural development. MREP was launched in 1992 by DOE and USAID and is managed by Sandia National Laboratories (Sandia) (Richards *et. al.*, 1999). Given that PV water pumping was largely unknown in Mexico and had a relatively poor reputation prior to 1994, US$2.2 million of USAID pilot hardware funds were used to buy down the PV system risk from the users perspective and were leveraged by additional user cost-share buy-in (~US$1.8 million) and additional Mexican agency implementation and administrative support (~US$0.5 million). DOE funds supported MREP technical assistance to Mexican partners from Sandia, New Mexico State University (NMSU), Ecoturismo y Nuevas Tecnologias, Winrock International, and Enersol Associates. MREP worked with established Mexican agencies for project implementation, in particular FIRCO and the State of Chihuahua (Richards *et. al.*, 1999). The key application supported by MREP between 1994 and 2000 was for PV water pumping systems for livestock and community water supply, although additional projects included PV lighting, communication, education, ice-making, and refrigeration systems, as well as a few wind-energy projects (Romero Paredes *et. al.*, 2003).

After 10 years of MREP's PV water pumping system implementation, a review was conducted on over 1/5 of installed PV water pumping systems from late 2003 to early 2004. The objective of the review was to determine technical status, reliability, and user acceptance of systems after several years of owning and operating such systems. Typical installed system configurations included a PV array (~500 Wp on average), pump, controller, inverter (only for ac powered pumps), and overcurrent protection devices, generally installed in compliance with the Mexican national electric code (NOM-Norma Oficial Mexicana), which parallels the U.S. National Electrical Code (NEC).

2. <u>REVIEW OF PV WATER PUMPING SYSTEMS</u>

2.1 Survey Methodology

Field surveys began in July of 2003 and continued until March 2004. During these visits, either the owner or the responsible person operating the PV water pumping system was surveyed. A total of 44 questions were included and classified into eight sections, which were: (1) general demographic information and system specifications; (2) information of traditional pumping systems used prior to PV system installation (if any); (3) user perception of vendor and installers; (4) productive and commercial impacts as a result of the use of PV pumping systems; (5) environmental impacts as a result of the use of PV pumping systems (if any); (6) replication of additional systems; (7) user lessons learned, and; (8) other renewable energy applications.

The section (1) questions detail the general technical status and system acceptance based on user experience. Within this section, it was determined whether the system was operating properly, improperly, or not operating at all and why. Further, users were also asked about their perception of the system's productivity, reliability, and economical feasibility. In section (2), information about any previous traditional system was gathered. Such information included type and cost of fuel used, maintenance of equipment, and the number of years a traditional system of its kind would last. The questions in section (3) addressed end-user perceptions about the installers and vendors quality such as installation, training, post-sales service, and maintenance. Among the questions in section (4) were the type of productive use of water, which could vary from domestic, agricultural, livestock uses or some combination of these; and the benefits brought by replacing a conventional water pumping system with a PV system, if any. Section (5) included questions about user perception on environmental aspects: the first one concerned the reduction of pollution by replacing a conventional system by a PV system; the second concerned any negative impact of PV systems on the environment. Technology replication was considered in section (6). These surveys included aspects about any other PV installations in the local area that were performed as a result of the experience learned from the original system, the type of installations (such as water pumping, lighting, communication, water purification, or any other); and also if the original owner procured any other PV systems. In section (7) users were asked about general learning aspects about system installation, cost, operation, technical assistance, and technical knowledge. Finally in section (8), users were asked about their willingness to buy other renewable energy systems and financing options.

2.2 Technical Inspection

The PV water pumping systems were visually and electrically inspected for electrical performance and pumping productivity. Electrical measurements on the PV array and the controller/inverter were made at the same time to determine water volumetric rate and solar radiation. Wiring, connectors, insulation, junction boxes, breakers, and water pipe were also inspected. Technical field inspections were carried out by engineers from FIRCO, NMSU, and EcoTursimo y Nuevas Tecnologias as shown in Fig. 1.

3. RESULTS AND DISCUSSIONS

Table 1 presents a summary of the 206 PV water pumping pilot systems that were installed under MREP in Mexico. A total of 101 kW of PV were installed benefiting 9,389 people. For the first three years, MREP was cost-sharing about 80 percent of total system costs. After 1996, Mexican counterparts were convinced of the effectiveness of PV technology for water pumping; thus, their willingness to pay gradually increased from about 20 percent up to 85 percent, dropping MREP cost-sharing to only 15 percent by 2000. After 2000, FIRCO has installed over 600 additional PV water pumping systems to date under a World Bank/GEF Renewables for Agriculture Program in Mexico.

Fig. 2 presents the average cost in dollars per watt of the PV water pumping pilot systems by state and installation year of MREP systems. The continuous line corresponds to the average cost for the installed systems in the State of Chihuahua. During the introduction of PV technology for water pumping, the cost was 22 and 25 dollars per installed watt in 1994 and 1995, respectively. After 1995, a decrease in cost reflecting PV market maturity was observed. By the end of 1999, the average cost was US$12/Wp. Over 40 systems were installed in Chihuahua. Similar results were also seen in Baja California Sur with 40 installations. In other states, the program implemented only a few projects and the PV market had not sufficiently matured and there was less vendor competition. MREP experience shows that key factors for achieving a mature market include training, program size, multiple vendors, quality workmanship, code compliance, and technologies deployed.

A total of 46 of the original 206 installed PV systems (22 percent) were surveyed to determine reliability and user acceptance of PV technology after owning and operating them for as much as 10 years. The survey was conducted in the states of Baja California Sur, Chihuahua, Quintana Roo, and Sonora.

Fig. 1: FIRCO engineer conducting performance evaluation of an 8-year old PV water pumping system at Rancho Jeromín, Chihuahua.

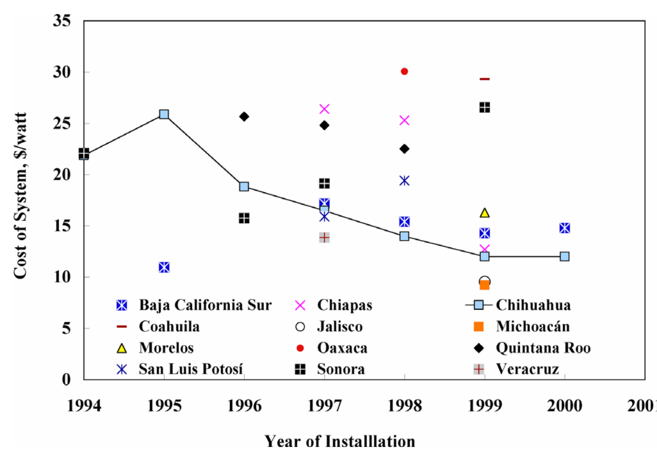

Fig. 2: Average cost of systems by year and by state.

TABLE 1: TOTAL MREP INSTALLED PV WATER PUMPING SYSTEMS IN MEXICO

	1994	1995	1996	1997	1998	1999	2000	
	Total per year							Total
kW installed	1.8	2.5	16.9	34.4	26.4	16.6	2.6	101.1
Number of Systems	6	5	24	66	59	41	5	206
Direct Beneficiaries	482	242	1,511	2,705	3,009	1,400	37	9,389
	Average per year							Average
System Size, W_p	300	507	704	521	446	404	514	491
$/Watt	$22.01	$22.87	$18.96	$19.06	$19.81	$22.49	$14.77	$19.98
MREP Cost-Share	78.1%	86.5%	82.9%	63.1%	41.9%	36.4%	15.0%	57.6%
Mexican Cost-Share	21.9%	13.5%	17.1%	36.9%	58.1%	63.6%	85.0%	42.5%

Fig. 3 presents the results obtained from the questions in section (2). The first bar shows that 55 percent of users agreed that the PV water pumping systems were very economical, 39 percent thought economical, 4 percent answered that they were adequate, and only 2 percent did not believe that PV systems were economically viable. Fully 48 percent of users thought that PV systems had excellent reliability, while 37 percent classified the systems with good reliability. Thirteen percent indicated that the systems had adequate reliability, while 2 percent did not classify the systems as reliable. Interestingly, some people responded this way even despite the fact their PV systems were actually not functioning at the time of the survey. For instance, in Rancho San Miguel in Baja California Sur, the ranchers blamed the system failure on the pump that failed after 7 years of operation and were satisfied that the solar system is reliable. In a number of cases, the ejido (farmers on communal ranch lands) mindset is that the Mexican government should replace any failed pumps, etc., and often are not willing to take on this responsibility themselves. The ranchers in San Miguel have gone back to using diesel pumps and are now awaiting government support, even though if the four families contributing US$400 each can buy the required replacement PV pump and eventually save the funds now spent on diesel fuel in only a year or so.

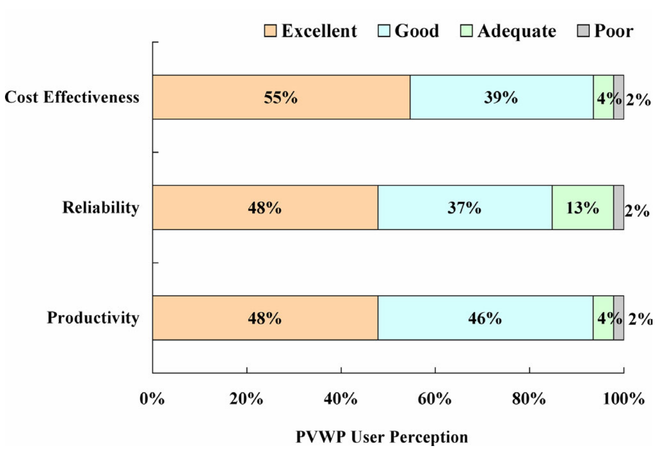

Fig. 3: User perception about cost effectiveness, reliability, and productivity of PV water pumping systems.

Regarding water production, 48 percent of users classified water production as excellent, 46 percent thought the water production was good, 4 percent felt that the amount of water pumped was adequate, and 2 percent were not satisfied with the water production. Before installing PV systems, 72 percent of the visited ranches had conventional pumping systems using gasoline, diesel, car engines, and one used an animal traction system. The typical consumption of gasoline for pumping water ranged from 5 to 10 liters per day for the states of Baja California Sur, Chihuahua, and Sonora. In the state of Quintana Roo, the consumption ranged from less than one liter per day up to 2.5 liters. Northern Mexico is an arid and hot region; livestock and crop production requires more water. Gasoline systems also required about 3 liters of lubricating oil per month. According to user's responses, a conventional gasoline or diesel system only lasts from 4 to 5 years. Solar pumps already exceeded this lifetime in many cases. Once the fossil fuel powered systems started to fail, they had to be repaired 2 or 3 times per year. People who were satisfied with the operation and productivity of PV water pumping systems mentioned that PV systems saved them money and time because there is no need to buy and transport fuel, less maintenance is required, and no time is invested in operating the systems on-site as was required before. The survey results found that over 4/5 of the rural Mexican users were satisfied with the reliability and performance of their PV water pumping systems

The majority of surveyed users in Baja California Sur, Chihuahua and Sonora responded that the work done by vendors and installers ranged from good to excellent regarding installation, training, post-sales service, and the operation and maintenance manual. On the contrary, in the state of Quintana Roo, these answers ranged from bad to adequate on vendor performance (with only two exceptions).

Due to a severe decade long drought in Northern Mexico, the desert ranches in Baja California Sur, Chihuahua and Sonora identify water as a larger issue than in tropical Quintana Roo. Regarding the productive uses of the water, from the 46 surveys, it was found that 100 percent used the water for livestock watering, 13 percent also used it for irrigation and 19 percent for domestic uses.

A representative example of successful PV water pumping pilot systems is at Rancho El Jeromín in Chihuahua. The system at Rancho El Jeromín was installed in 1995 utilizing an ASE Americas 848 Wp array to pump 12.5 m^3/day of water daily via a Grundfos pump operating at 40 m total head. The system has not had a single component replaced and has pumped water daily as designed for the past eight years. Full PV system payback was realized in only 2.5 years. Fig. 4 presents the life cycle cost analysis for the PV system installed at Rancho Jeromin compared to the conventional diesel system previously used. Since the solar system installation, the owner has saved over US$15,000 in fuel and maintenance, and the PV system should still provide many years of service to come.

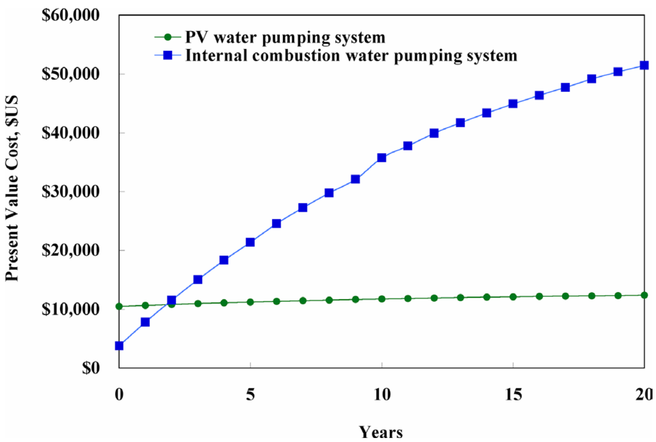

Fig. 4: PV system payback realized in 2.5 years for the Rancho El Jeromin solar vs. diesel powered pump.

The average installed time for all the systems surveyed was 6.5 years. The oldest systems were installed ten years ago and included the review of the very first system installation in Estación Torres, Sonora utilizing a Grundfos SP3A-10 solar pumping system installed by Applied Power. This system has been operating daily since 1994 with no parts replaced or maintenance of any kind.

Of the systems surveyed in Baja California Sur (10), Chihuahua (11), Quintana Roo (13) and Sonora (12), 25 of the systems were operating as designed (eight with maintenance actions previously taken), three were operating at reduced water production, and 18 were not operating, two of which had been dismantled. Fig. 5 shows the performance of the surveyed systems by state. This plot indicates that Sonora achieved the highest success rate (84%), followed by Chihuahua (64%), Baja California Sur (60%), and finally Quintana Roo (31%). In Sonora and Chihuahua results found that 8 and 9 percent of the surveyed systems were operating at reduced water production capacity (caused when submersible centrifugal pump stages have filled up with silt, which is easy to correct). Regarding the non-functioning projects, the breakdown was Sonora (8%), Chihuahua (27%), Baja California Sur (40%), and Quintana Roo (69%) with the most failures. Since water pumping is not as critical in Quintana Roo as in the northern desert states, system repair is not viewed as critical to the survival of livestock. Most of the water pumping systems can be restored to service with the simple replacement of a failed pump or controller.

For example, a SolarJack pump had been replaced for the Los Tepetates Ranch in Baja California Sur. The 770 Wp system was designed to pump 15 m^3 of water daily at a total dynamic head of 15 m. Although the pump had been replaced once after six years of operation, the users were still satisfied with the PV system performance reporting that it had saved them significant time and money over the long-term and that the pump replacement was worthwhile.

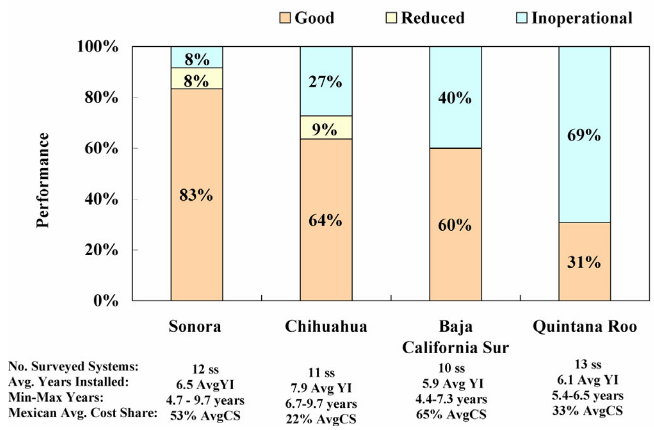

Fig. 5: Performance of surveyed systems by state.

PV water pumping system failures were typically technology and installer specific. As mentioned, 18 systems were not operational and 26 component failures were documented (eight had been repaired by the owners and were again functional). Fig. 6 presents the type of failures that occurred. Most failures were due to defective equipment. Of the 26 failures, 54 percent occurred with pumps; 21 percent with controllers/inverters; 17 percent were due to well-related failures (e.g., drying out or well collapse); and 8 percent of systems were dismantled due to theft or the death of the owner and the children no longer wishing to ranch.

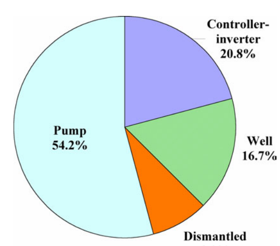

Fig. 6: Type of failures encountered of the 26 system failures from the surveyed PV pumping systems.

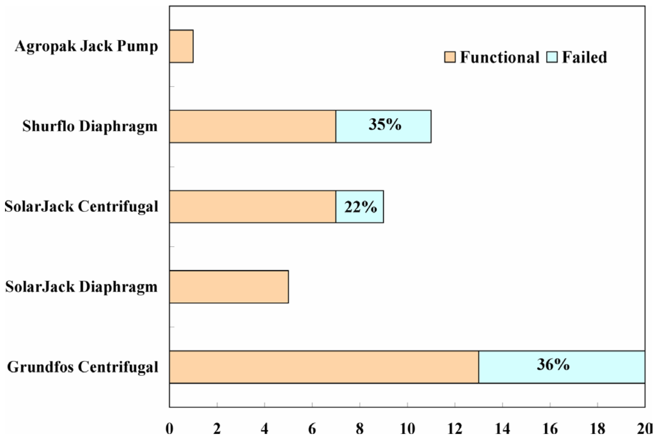

Fig. 7: Number of functional and failed surveyed pumps.

The PV modules were found to be the one of the most reliable system components. The technical evaluations showed that PV modules, tracking systems, and wiring had not failed. Electrical measurements on PV arrays showed that they were working within design specifications and warranties. Of all 46 systems surveyed, no PV modules had failed. Five out of the 46 surveyed systems had passive tracking systems that were all functional.

4. CONCLUSIONS

PV water pumping systems installed under the USAID/DOE Mexico Renewable Energy Program have demonstrated that long-term reliability is achievable for this application. The PV systems have proven to be an excellent option in meeting water pumping needs in rural Mexico where electrical grid service does not exist. Investment payback for the PV water pumping systems has averaged about 5-6 years, with some systems reporting paybacks in half that time.

The survey of 46 PV water pumping systems assessed in Baja California Sur, Chihuahua, Quintana Roo, and Sonora found that the majority of systems were still functioning after as long as 10 years. When there have been problems with these systems, they are mostly due to failure of pump controllers and inverters, as well as extenuating circumstances such as well collapses and wells drying out due to drought.

There were no PV module failures across a wide variety of PV module types and brands used in the different water pumping systems. The survey results found that over 4/5 of the rural Mexican users were satisfied with the reliability and performance of their PV water pumping systems. During the first years of installations, MREP invested in training workshops for installers, vendors, engineers, and users of PV which ultimately paid off with a majority of functional systems after many years of operation.

5. ACKNOWLEDGEMENTS

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